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14. ABSTRACT

Initial collaborative observations and modeling of a warm effluent plume (Calvert Cliffs Nuclear Power Plant) suggest that coherence length scales in both models and observations are similar leading to confidence in the models for AUV decision making.

Studies were initiated to determine if algorithms could be developed that could process current fields and find regions of very low current speed. Tests of the algorithm on a two-dimensional simulated velocity field worked well with true stagnation points found and with no 'false alarms'.

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ONR Project 254921

Final report

I. Executive Summary

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Studies were initiated to determine if algorithms could be developed that could process current fields and find regions of very low current speed. Tests of the algorithm on a two-dimensional simulated velocity field worked well with true stagnation points found and with no 'false alarms'.

II. Introduction

This report covers the initial project working with colleagues at Virginia Tech where we made observations and develop fine scale models in conjunction with their AUV studies. After that we report on progress working with colleagues at UDel on stagnation point and center of eddy studies.

III. Comparison of observations with a model of a warm water discharge into Chesapeake Bay

Introduction

The overall goal of this project is to develop and test techniques for assimilating data from underwater and surface autonomous vehicles in addition to the usual sources of Eulerian and Lagrangian systems into a small scale coastal (or estuarine) circulation model. The effort was to focus on communication from the various sensors, assembly of data into gridded fields (if appropriate), generation of nowcasts and projection of information with forecasts.

The project evolved to focus on the comparison of the statistics of models compared to that of real data. By doing this the control systems may use statistical measures of real-time data to improve overall system control. The following reports on this topic.

OBJECTIVES

The objective was to develop a method to deterimine integrative statistics such as variance distributions and spatial correlation functions related to turbulence in the thermal plume. These statistics are then used to better control the AUVs in their detection algorithms, which are different from the gradient climbing approaches.

APPROACH

The approach involves several parallel tasks.

Assimilative Modeling – The principle model used was the Rutgers/UCLA Regional Ocean Model System (ROMS). The NOAA Coast Survey Development Lab's implementation of the QUODDY finite element model (C3PO) was used to provide velocity and sea surface height at the model open boundaries. Key Personnel were John Klinck, Mike Dinniman (Technical Staff), Chester Grosch, Andres Tejada (Post-Doctoral Associate).

Statistics and Spatial Correlation Functions – Surveys were made in collaboration with VT to gather data to determine statistics and spatial correlation functions. The surveys mainly were ADCP time series and were spatial in nature to determine spatial correlation. Occasional CTDs were used for vertical gradient determination. Key Personnel are Larry Atkinson, John Klinck, Isaac Schroeder, Diego Naveraz, Jose Blanco (Post-Doctoral Associate), and David Salas (Graduate Student).

Model Configuration

The numerical circulation model used was the Rutgers/UCLA Regional Ocean Model System (ROMS) (Shchepetkin and McWilliams, 2005; Haidvogel et al, 2008). ROMS is a free-surface, finite-difference, hydrostatic primitive equation ocean circulation model with a terrain following vertical coordinate. A conservative parabolic-spline discretization was implemented in the vertical in order to reduce the pressure gradient error that can often be a problem in terrain-following coordinate models (Shchepetkin and McWilliams, 2003). Momentum advection was computed with a 3rd-order upstream-biased advection scheme (Shchepetkin and McWilliams, 1998). Tracers (temperature and salinity in this case) were advected with a monotonized, fourth-order, centered scheme (Shchepetkin and McWilliams, 2003). Vertical mixing was simulated with the k profile parameterization (KPP) vertical turbulence closure scheme (Large et al., 1994) including surface and bottom (Durski et al., 2004) boundary layer mixing. No explicit horizontal mixing of momentum or tracers were used. Quadratic bottom stress with a coefficient of 1.0×10^{-3} (non-dimensional) was applied.

The model domain (Figure 1) covered a 3 km by 4 km area of the west-central Chesapeake Bay centered on the cooling water discharge channel from the Calvert Cliffs Nuclear Power Plant located near Lusby in Calvert County, Maryland. The model grid was oriented to be along the axis of the discharge channel. The horizontal resolution was a constant 15 m and the model had 20 vertical layers that were uniformly spread throughout the water column if the bathymetry was less than 5 m and then slightly concentrated towards the surface and bottom for deeper water. One experiment was also performed with a 10 m horizontal resolution grid. The bathymetry was from the National Geophysical Data Center 3-arc-second Coastal Relief Model with some modifications made for the intake and discharge channels. In the model domain, the bathymetry ranged from 2 to 14 m leading to a maximum depth of the model surface layer of 0.46 m.

Model initial conditions were based on observations in the area in mid-August (Lacy, 1979) with a constant temperature of 26.7 C and a vertical salinity profile

that was a uniform 9.8 psu above 5.8 m and then increased linearly below this at a rate of 0.45 psu/m. Wind stress was applied based on a constant wind of 4.1 m/s (8 knots) from due south (roughly equivalent to the observed wind during the field observations). Surface heat and fresh water fluxes were set to zero.

Tidal sea level and depth average velocity were imposed on the model open boundaries using the five most significant harmonics (M2, O1, N2, K1, S2) from the NOAA Coast Survey Development Lab's Chesapeake 3-D Physical Oceanographic Model (C3PO - http://nauticalcharts.noaa.gov/csdl/op/c3po.html) simulation of the bay using the QUODDY (Lynch et al., 1996) finite-element model. Note that other than the discharge jet, the observed predominant currents in the area under typical wind conditions are the tidal currents (Lacy, 1979).

A two-dimensional radiation scheme was used at the open boundaries for the baroclinic velocity components and the tracers with adaptive nudging also used for the tracers (Marchesiello et al., 2001).The time scale of the boundary nudging was set to 1 day and the tracers were relaxed to the initial values.

The power plant has two nuclear units and has a once-through cooling system which draws in water from the bay below a curtain wall at the plant intake. At full plant load, the cooling water is heated between 5 and 6 C (USAEC, 1973; Lacy, 1979). This water is discharged through four 3.8m by 3.8m concrete conduits that rest on the bay bottom about 250 m from the shore. The tops of the discharge conduits are about 1.8 m below the water surface and the velocity through each conduit is about 2.7 m/s (USAEC 1973; Schreiner et al., 2002), leading to a total volume flux of 156 m^3/s from the discharge channel. The discharge channel was implemented in the model as two point sources of volume flux (78 m^3/s each) that are each one grid cell wide and in the vertical have flux into the water from 1.72 m below the mean surface to the bottom (4.30 m). The temperature of the discharge water is set to a constant 32.0 C (5.3 C above ambient) and the salinity is set to 9.8 psu. The velocity of the discharge jet at the conduit mouth is smaller than observations (2.0 m/s vs. 2.7 m/s), but it was thought to be more important to have the top location of the plume with respect to sea level, the total discharge volume flux and the total discharge heat flux be accurate (having all four quantities match would require a drastic modification of the bathymetry in the area).The model simulation was run for 36 hours and model fields were saved every 20 minutes.

Figure 1 shows the results of a run using similar tide and wind parameters as occurred during the observation period.

Results of Model Runs

The Rutgers/UCLA Regional Ocean Model System (ROMS) is being used to create a model for a region (3.9 km by 3.0 km) in the Calvert Cliffs area. This will be the grid for the future assimilative modeling, but is being used now for some preliminary studies of

the high temperature plume of cooling water discharged from the Calvert Cliffs plant. The model grid has high horizontal resolution (15 m) and has 20 vertical levels. The bathymetry for the region was taken from National Geophysical Data Center Coastal Relief Model. Some modifications were made by hand to account for the intake and discharge channels. The model is forced winds at the surface and by velocities and surface heights at the lateral open boundaries representing the tidal flow in Chesapeake Bay. There are currently no surface heat or salt fluxes. Figure 1 shows the results of a run using similar tide and wind parameters as occurred during the observation period.
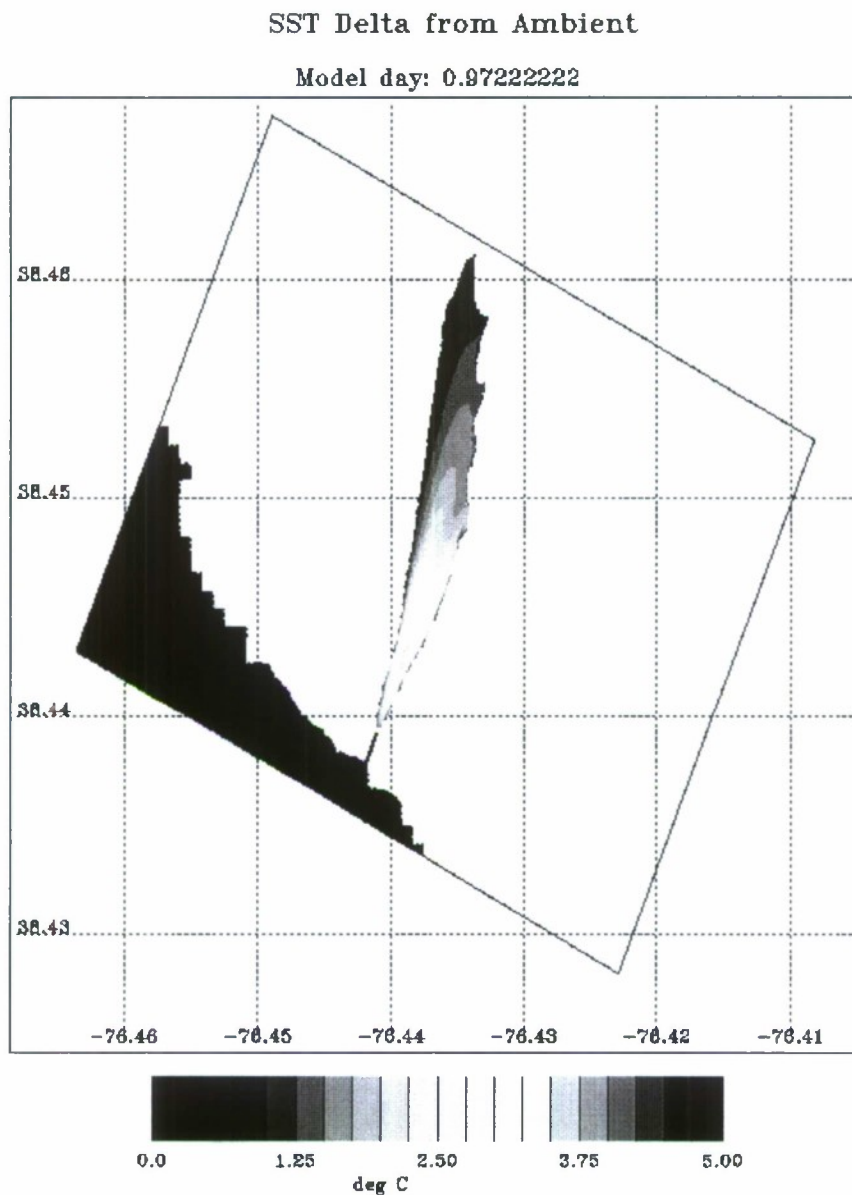
Figure 1. ROMS model simulation of the thermal plume emanating from the power plant at tide stage similar to when data was taken (Figure 2). No contours below 1.0°C above ambient are shown.

Field survey completed in 2005 – A one-day survey of the thermal plume was accomplished in early September. A towed ADCP/CT system and occasional CTD profiles were used to characterize the discharge area and the plume both near and far field. Additionally Dr. Stilwell and students came on board to observe our techniques for acquiring data and real time processing. This was a very valuable experience for all involved. Figure 2 shows one of the surface SST fields derived from our survey.
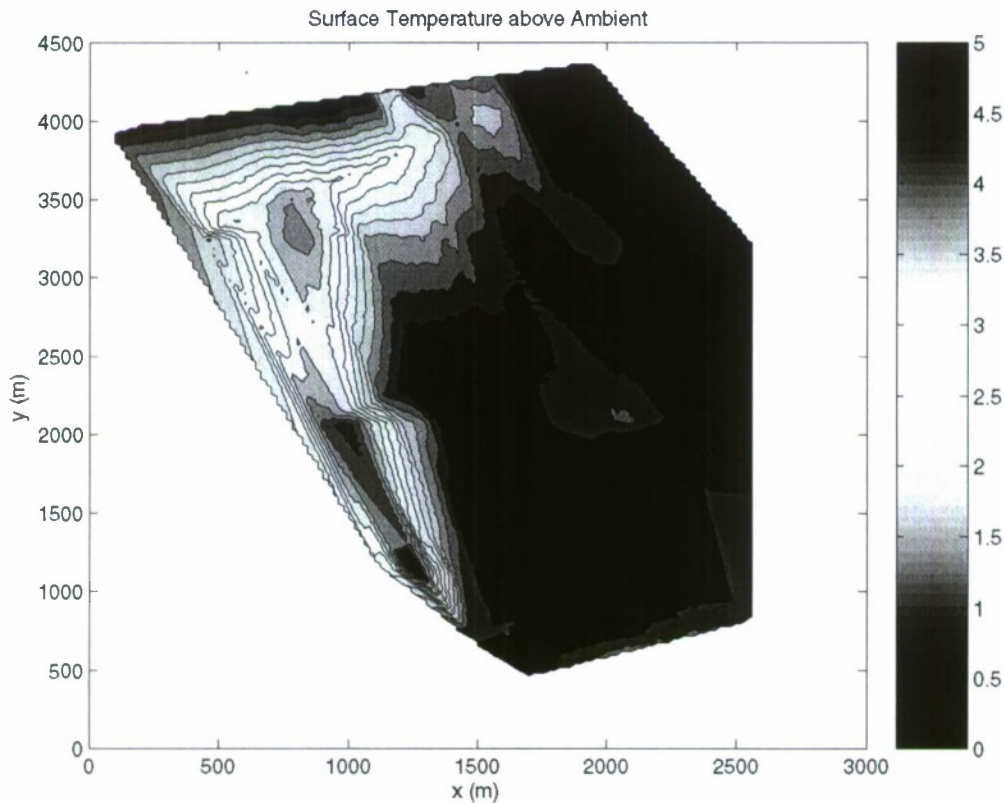

Figure 2. Surface temperature derived from towed ADCP/CT system. The source of the thermal plume is the darkest red. The tide was flooding sending the plume northward.

Realtime data needs assessed – Although we originally proposed two ADCP moorings to provide velocity data for the model further testing and model runs suggest we would not need the mooring data.

Statistical comparison of model and real data

A key test of the model is a comparison of it with the ADCP data. Figure 3 shows data from the observations and Figure 4 shows data from the model run.
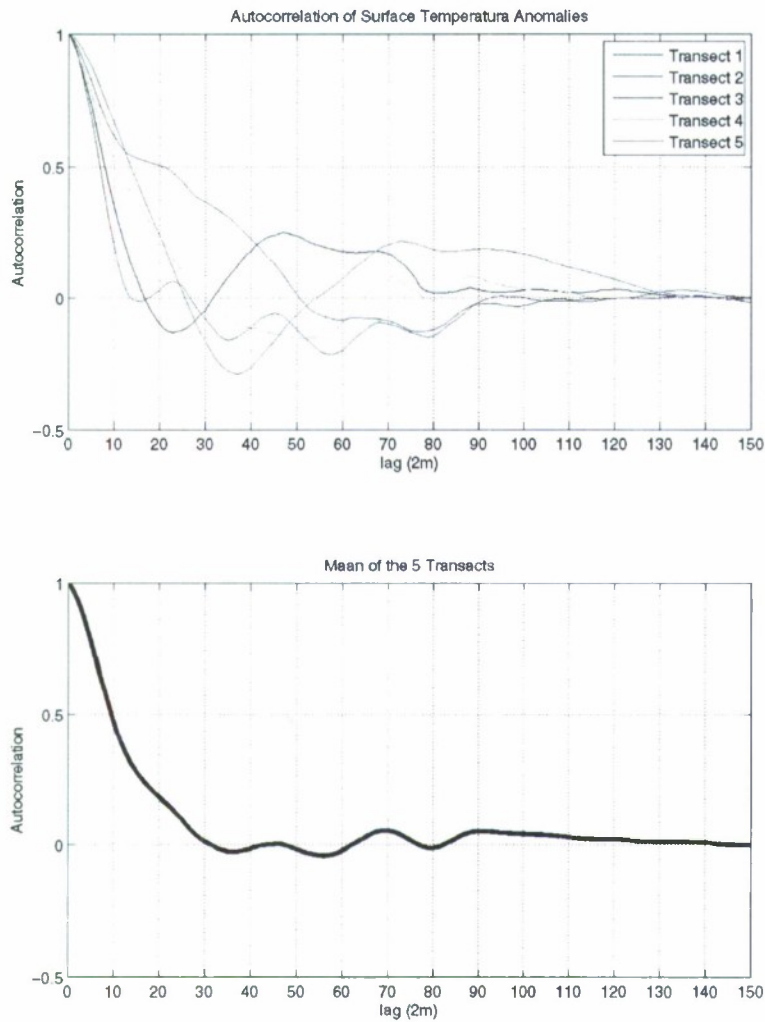

Figure 3. Five realizations of the autocorrelation function. These were calculated from the temperature data obtained during five passes across the outflow. The spread in the results is to be expected because of the turbulent structure of the outflow jet.
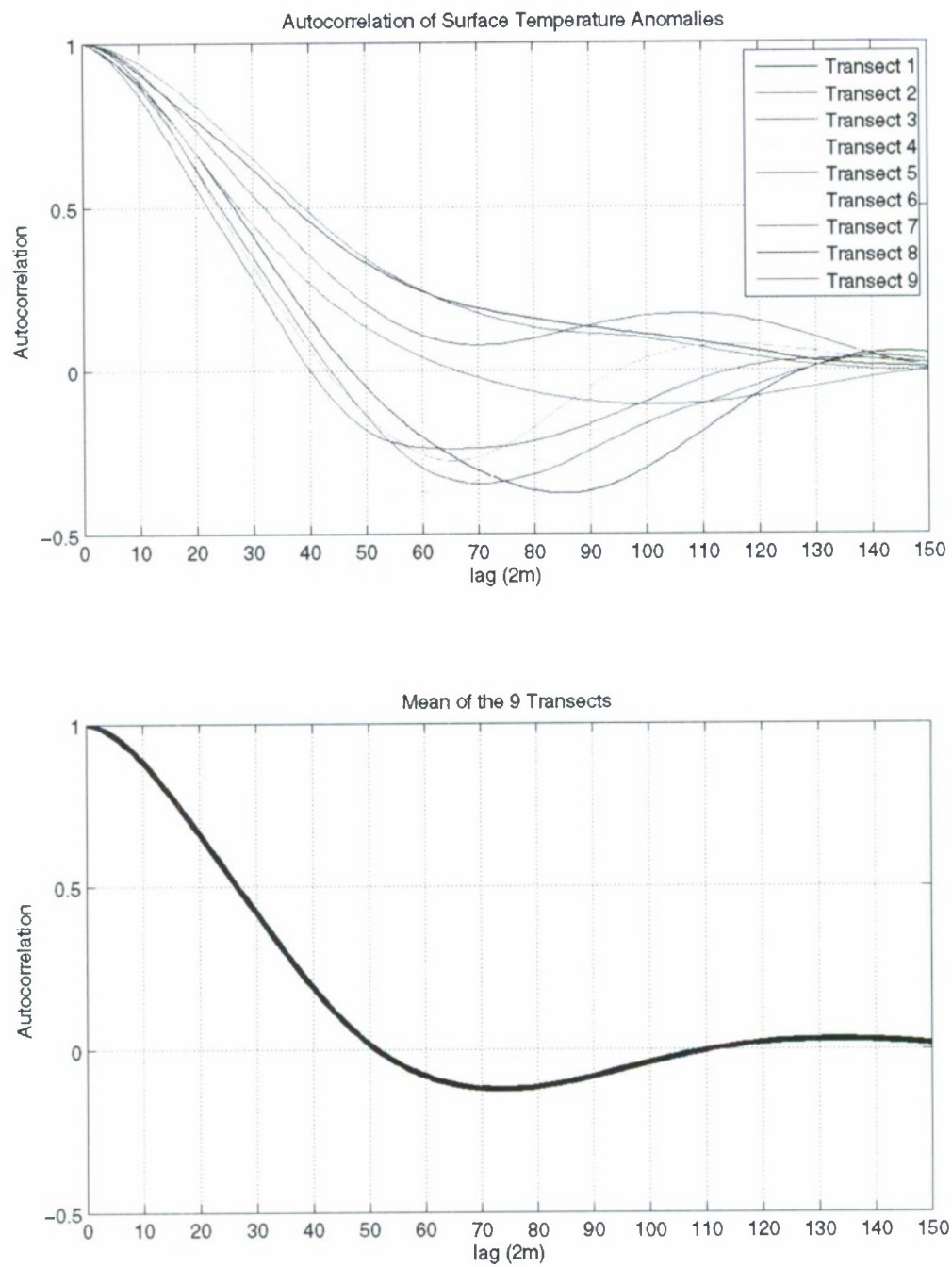
Figure 4. Autocorrelation from the 9 transects in the model.

Figure 4 shows nine realizations of the autocorrelation function obtained from the model. In both figures the dashed (upper panel) and the solid (lower panel) are the average of these realizations. There is reasonable agreement between the results obtained from the data and those from the model. However, the first zero crossing of the data autocorrelation is at approximately 60m while that from the model is at about 100m. This indicates that there is probably somewhat too much damping in the model.

IV. Stagnation Point and Center of Eddy Studies

The original proposal called for emphasis on field work providing data for models that would interface with the research of Dr. Stilwell's group at VT.

We did one field experiment that was successful although not in ways expected. We implemented a very fine scale ROMS model of the Calvert Cliffs nuclear plant plume that was then compared to our ADCP data. We found surprisingly good comparisons.

Further discussions with Dr. Stilwell and new discussions with Drs. Kirwan and Lipphardt at University of Delaware led us to take an approach that interfaces with both Dr. Stilwell and Drs. Kirwan and Lipphardt.

For the final year of our research on this project we continued our collaboration with Dr. Stilwell and students and add collaboration with Drs. Kirwan and Lipphardt. This will make the most effective use of our research skills and may add useful research to the University of Delaware effort.

We proposed to focus on algorithms which can process the current field with little or no human intervention and find regions of very low current speed. It appears that the regions of very low current speed, away from boundaries, must fall into one of two classes (1) near stagnation points, and (2) near the centers of eddies. Dr. Grosch has been working on algorithms which can detect one or the other. The next step is to test these algorithms on flows for which, in a sense, the answer is known. In addition, there may be better algorithms. The results of his collaboration with Drs. Kirwan and Lipphardt are as follows:

In certain circumstances it is desirable for an AVU to remain within a given volume with minimum power expenditure. One obvious stategy is to find regions within the volume where the velocity is very small, that is near stagnation points. It is necessary to develop one or more algorithms which can be used on velocity fields obtained from a model and/or observations. The algorithm should be robust and easy to implement without human intervention.

A possible algorithm is being implemented and tested. This algorithm can be described as follows. Choose a small magnitude, ε, not exactly zero to define a near stagnation point. Assuming that the velocity data is given on some, not necessarily uniform grid, step across the grid computing the velocity magnitude at each point and comparing it to ε. If the velocity magnitude is less than ε that grid point is a near stagnation point.

In the more likely situation that a near stagnation point is not located at a grid point an extrapolation procedure into space near a grid point can be used. Let

$u_i, i = 1,2,3$ denote the velocity field. The velocity at a gridpoint $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$ is $(u_1^{(0)}, u_2^{(0)}, u_3^{(0)})$. An approximation to the velocity components in the vicinity of $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$ is

$$u_i = u_i^{(0)} + S_{i,j}^{(0)}(x_j - x_j^{(0)})$$

with summation over j and $S_{i,j}^{(0)}$ the rate of strain tensor at $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$.

$$S_{i,j} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$

If a near stagnation point lies in the vicinity of $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$, then its location can be found from

$$\varepsilon = u_i^{(0)} + S_{i,j}^{(0)}(x_j - x_j^{(0)})$$

One can check that this is a valid near stagnation point by testing whether or not the location determined is within a sphere of radius R of $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$ with R a fraction of the distance to the nearest neighbor of $(x_1^{(0)}, x_2^{(0)}, x_3^{(0)})$.

This algorithm was coded and tested, first on a two-dimensional analytic velocity field which has a stagnation point, next on a two-dimensional simulated velocity field. The two-dimensional simulated velocity field was a slice thru a Direct Numerical Simulation of decaying isotropic turbulence at a Reynolds number based on the Taylor microscale of about 50. The algoritm worked very well, true stagnation points were found and there were no "false alarms".

As the project has progressed the areas of fruitful research has changed also. One of those new areas has been adapting models to optimize the locational control of an AUV.

The good comparison between the model and data suggests that we are on the right track to improving the control algorithms via statistical analysis of the real time data acquired by the AUV.

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